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NOTES ON "HIGH LOSS EFFECT" IN RF CAVITY TUNING FERRITE

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Introduction

In the early stages of design of accelerating cavities for the FNAL synchrotrons a program was initiated for testing a variety of ferrite materials for their suitability in tuning rf systems at high power levels. In those tests on anomalous rf power loss phenomenon was discovered.[1] It appeared when the ferrite was operated above a certain rf power level. The effect was observed both at FNAL and at CERN[2] and has been named "high loss effect" (HLE). Since the threshold for the onset of high loss effect is lower at low dc biassing fields it has been suspected for a long time that the effect was responsible for a limitation of booster rf cavity gap voltage which occurs near the beginning of the booster acceleration cycle, where the biassing dc field is low.

In order to improve the performance of the booster rf system there has been an effort to locate a substitute ferrite which will allow adequate tuning range without the attendant voltage limitation which now exists. Tests have been completed on a booster cavity using a different type of ferrite (Toshiba

type M4D21A). The overall performance of booster accelerating cavities can be substantially improved through the use of such ferrite and a comparison of "old" vs "new" performance will be presented in another note. It is the purpose of this note to present some new findings regarding "high loss effect" which have resulted from detailed comparison of cavities using the two types of ferrite.

In this note the "new" ferrite will be referred to as "type d" ferrite while the "old" ferrite will be referred to as "type c" (Toshiba M4C21A). In addition, reference to a third type of ferrite, "Stackpole" will be made. Many of the tuners studied contain a mixture of Toshiba and Stackpole ferrite. The threshold for high loss effect in Stackpole ferrite is known to be much higher than that for either type of Toshiba ferrite so when a tuner exhibits a high loss threshold it is assumed that it is the Toshiba ferrite which is creating the effect. It is necessary to incorporate Toshiba ferrite in tuners because of its relatively higher incremental permeability μ. Use of Stackpole ferrite alone would not allow sufficient tuning range in the cavities. Each "standard" accelerating cavity is tuned by tuners containing a total of 30 Toshiba ferrite cores and 54 Stackpole cores of the same geometry. The ferrites are Ni-Zn type ferrite toroids 20.3 cm o.d., 12.7 cm i.d. by 2.54 cm in length (500 c.c.) each weighing approximately 2 kg. In normal accelerating cavity operation

the ferrites are initially biassed to saturation and subsequently operated on that part of their magnetization curve between the remnant field and saturation. During operation the incremental permeability of the tuning ferrite varies typically from a value of near 11 to the lowest possible value of perhaps 1.6.

Measurements and Observations

1. Testing Procedures

Measurements were made on two booster accelerating cavities which were identical in all respects other than that the tuners on one cavity contained type c ferrite and the other type d ferrite. The cavities were operated at resonance at a series of fixed frequencies between 30 and 50 MHz on a time cycle such that the cavity was excited for 10 msec out of each 30 msec. Because about half of the energy stored in such a resonator is stored in the ferrite, the Q of the system is dictated by the Q of the ferrite, ranging from about 200 at 30 MHz to about 1000 at 50 MHz where the ferrite is heavily biassed. The cavities were excited with a standard 100 kW power amplifier in which the anode voltage and rf power level were separately adjustable. At any setting of the anode voltage the presence of an rf voltage swing nearly equal in peak amplitude to the dc anode voltage is indicated by a sharp rise in power amplifier screen grid current as the rf drive level is increased. For

any dc anode voltage the rf voltage was standardized at that level.

Figure 1a, and 1b show the rf envelope during the 10 msec on period just below the level of HLE onset and at a power level where HLE is fully developed. Also shown in the figure is a signal which represents the phase error between the rf voltage developed on the cavity and the rf drive current. This signal is representative of the extent to which the cavity may be detuned during the excitation period. High loss effect typically has the characteristics seen in the photograph. The rf amplitude comes on at some level, remains there smoothly for a few milliseconds, then suddenly drops to a somewhat lower level where it remains, exhibiting a characteristic noisy amplitude during the remainder of the cycle. The time of onset of high loss effect becomes earlier as the initial power level is increased but there is always a short period of normal operation preceding the onset. While the phase error appears more noisy during the high loss period it never indicates a net detuning of the cavity resulting from high loss, even when there is no automatic tuning feedback system in operation.

Another characteristic of high loss effect can be seen in Fig. 1. Immediately following the removal of rf power from the system there is a small burst of oscillation lasting for a few microseconds. A series of "follow-on"

rf bursts are shown in more detail in Fig. 2. Such a follow-on burst always accompanies high-loss effect and its amplitude is proportional to the extent of high-loss development or rf "over-drive". Expanded scale observation of the follow-on burst shows it to be sinusoidal consistent with the cavity resonant frequency. The follow-on pulse burst amplitude shown in Fig. 2d can be matched nicely by an expression of the formulae:

$$A(t) = A_o \ (1-e^{-t/T_1})e^{-t/T_2}$$

if the rise time constant T_1 is 2.2 μsec and the decay time constant T_2 is close to 21 μsec. The measurement was done at 35 MHz where the Q of the cavity was measured to be 245. The cavity time constant $2Q/\omega$ is precisely consistent with the rise time constant of the follow-on burst, as if the ferrite, having somehow stored some energy, were delivering it back to the cavity with its normal Q. The longer decay time constant, at this frequency, is consistent with a Q of 2300. Nothing in the system is known to have a Q that high. The implication is that in high loss effect the ferrite is actually coupling energy to some other mode where it is stored with quite high Q. Upon removal of external excitation some fraction of the stored energy is delivered rather slowly back to the cavity.

2. Threshold Measurements

Using the easily observable follow-on pulse and the first indications of amplitude degradation as indications the threshold for the onset of high loss effect was observed for the two types of ferrite at a variety of frequencies within the operating range. The results, plotted as a function of rf voltage swing at the power amplifier anode, are shown in Fig. 3. Between 30 and 35 MHz it appears that the type d ferrite requires slightly more rf voltage than the type c while at higher frequencies there is no significant difference between the two.

Because the type d ferrite has an incremental permeability about half that of type c the dc biassing field required to reach each frequency is different for the two types of tuner so that comparison at a given frequency may not be particularly meaningful. A more revealing comparison might be to compare the onset of high loss to the magnitude of rf flux swing in the ferrite, or to the energy stored per core, or the energy dissipated per core.

Figure 4a shows the power dissipated and the rms rf flux in the worst case core at the onset of HLE as a function of biassing field. The type c cores have a peak in the μQf curve at about 35 MHz and consequently dissipate less power at the threshold than do the type d cores. In Fig. 4b the stored rf energy per core at the onset of HLE is

shown for the two standard tuners and also for data taken from a cavity fitted with a single 20 core tuner containing entirely type d ferrite. The error flags represent a composite of measurement error and error introduced in the somewhat approximate calculations required to determine the worst case rf current in each tuner. These data can be construed to indicate that the onset of high loss effect occurs when the rf stored energy is near 1.5×10^{-4} Joules per core somewhat independent of the dc biassing field, the rf frequency, and the type of material.

3. Temperature Effects

Thresholds for the onset of HLE were made at 25, 30, and 35 MHz using a single tuner containing 20 type d cores. These measurements were made at 35°C and repeated with the tuner cooling water raised to 80°C. No significant differences were observed in the rf threshold levels at these two temperatures. Slight changes were, of course, required in the dc biassing currents to compensate for temperature dependance of the ferrite incremental permeability, but such changes simply readjust the tuner impedance to the same value for each temperature so that the rf currents, stored energy, etc., remain unchanged. While some temperature dependance almost certainly exists the lack of an observable effect over this rather small temperature range indicates that there is no dramatic effect.

4. Study of Coherence

The fact that some period of normal operation precedes the onset of HLE and the surprisingly long decay time constant give rise to the suspicion that there is within the ferrite a large scale coherent energy storage effect. All studies were done at constant frequency excitation so that an adequate pumping mechanism existed for feeding energy into such a mode. In order to study this conjecture the excitation frequency was varied slightly during the 10 msec rf gate time with the intention of introducing a time spread which would disturb or destroy the HLE coherency. In the first test the rf frequency was modulated sinusoidally at about 1 kHz keeping the bandwidth of frequency modulation well within the bandwidth ($\Delta f = f_o/Q$) of the cavity. Figure 5 shows the effect of such modulation. In Fig. 5c the phase error trace indicates a phase deviation of about $\pm$ 8 degrees and HLE is completely eliminated. After introduction of frequency modulation such as this the rf power excitation amplitude can be raised to the maximum possible level without reappearance of HLE. As the modulation frequency is raised and the sidebands move away from the center frequency a decrease in the effectiveness of the HLE detuning might be expected. In tests it was found that if the modulation frequency was raised above 10 kHz a larger amplitude of modulation was required to defeat HLE and above 35 kHz the

required amplitude was larger than the 45 degree bandwidth of the cavity so noticeable amplitude modulation of the rf resulted. Tests were not carried further.

As the modulation frequency is lowered it begins to appear as a monotonic frequency sweep during the gate time. In Fig. 6 the results of a linear frequency sweep during the gate time are shown. If the frequency is swept at a rate greater than 18 kHz per msec the HLE coherence is completely eliminated as shown in part a of the figure. In order to prevent detuning during the monotonic frequency sweep the cavity was automatically tuned during the sweep by feeding the phase error signal back to the tuning current supply. In Fig. 6b the system is swept at 200 kHz per msec. The decrease in rf amplitude is not the result of HLE but instead it results from a degradation of ferrite Q resulting from sweeping the biassing field. The field is swept by the automatic tuning system in response to the developing phase error (detuning) signal. Later in the cycle the amplitude of rf increases due to an increase in system Q resulting from increasing ferrite saturation at higher bias.

5. Frequency Spectrum

The apparent existence of extraneous oscillatory modes within the ferrite might be verified by observation of the frequency spectrum of rf energy within the cavity during the occurrence of HLE. In Figs. 7a and 7b the output signal

from a spectrum analyzer connected to pick-up signals from the cavity are shown. In part a of the figure the fundamental 32.5 MHz signal and its first two harmonics are seen and in addition there is a strong signal near 84 MHz. The additional trace on the figure represents the applied frequency modulation. Part b of the figure shows the destruction of HLE by frequency modulation so that the amplitude of the cavity excitation is unchanged from the pre-HLE level. It is clear that the 84 MHz signal is removed by removal of HLE. Further tests in which HLE was destroyed by monotonic frequency sweep or simply reduction of excitation amplitude all corroborate the result that the 84 MHz signal is present only during HLE. In tests at other frequencies (and consequently other dc ferrite bias levels), it was found that the frequency of the 84 MHz signal tunes with applied dc field. In Fig. 8 the HLE spurious frequency is shown as a function of the applied biassing field. This frequency apparently bears no particular relationship to the resonant frequency of the cavity but at about 83 MHz it coincides with the second harmonic of the cavity frequency and the possibility of large direct harmonic excitation exists.

Conclusions

1. The high loss effect clearly exists and the threshold for its onset is apparently related to the stored rf

energy in the ferrite. This threshold does not vary drastically between c and d type ferrite and it is apparently not a strong function of the superposed dc magnetizing field nor is it a strong function of temperature.

2. High loss effect appears to be a large scale coherent oscillation within the ferrite which can be attenuated or destroyed by a form of Landau damping effected by introduction of frequency modulation on the exciting rf field. There is clear evidence that a spurious frequency excitation exists in the cavity as result of HLE but the frequency is not consistent with a simple model of spin wave excitation and it is apparently too high to be a magneto-acoustical phenomenon.[3]

3. Overlapping of the second harmonic of the booster accelerating cavity frequency with the characteristic HLE frequency contributes to a clearly evident second harmonic peak in the booster wave form during normal operation. This effect can be exacerbated by unnecessarily large power excitation of the cavity near the crossing frequency.

4. Because of the destruction of HLE by monotonic frequency modulation of 18 kHz per msec or greater, HLE is probably not related to booster cavity voltage limitation. The rate of frequency sweep during the early

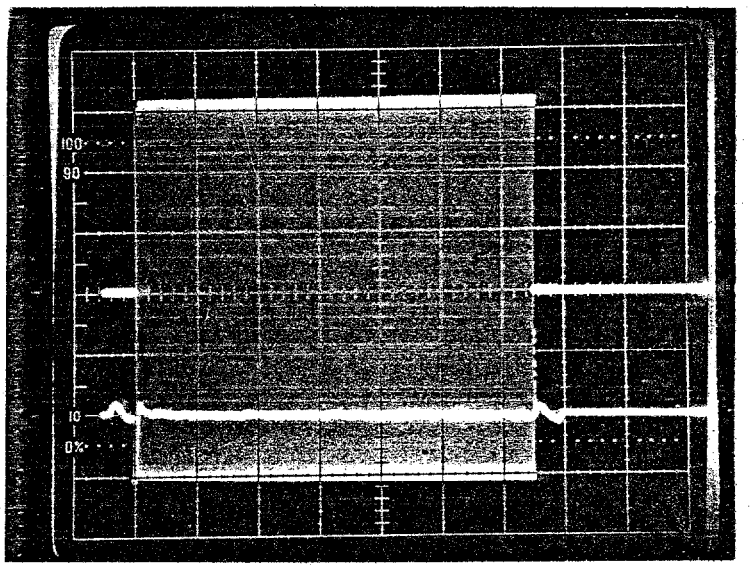
part of the booster synchrotron acceleration cycle is far greater than that necessary to destroy HLE.

References

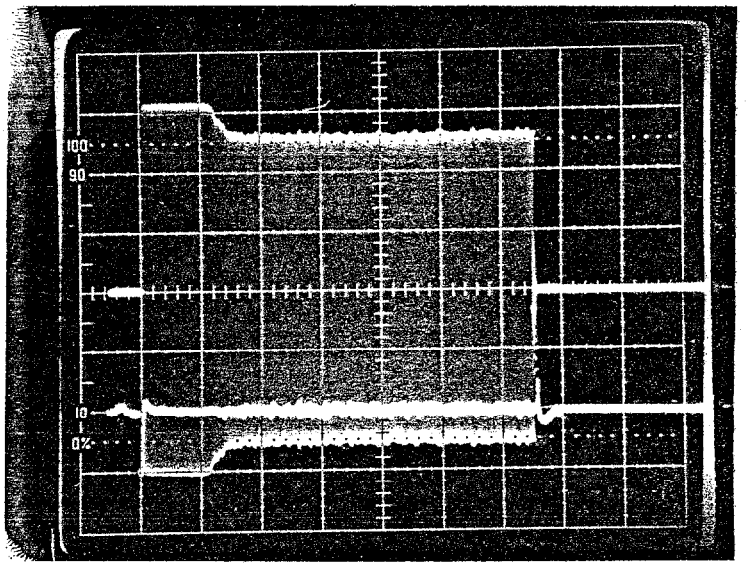
[1] Q. A. Kerns and B. R. Sandberg, The RF Ferrite Testing Program at NAL. IEEE PGNS NS-18 244 (1971).

[2] C. Arnaud et al., Finding Out About Ferrites. CERN COURIER 12 No. 11, pp. 364 (1972).

[3] S. Wang, Solid State Electronics. McGraw Hill Book Company 1966 pp. 606ff.



(a)

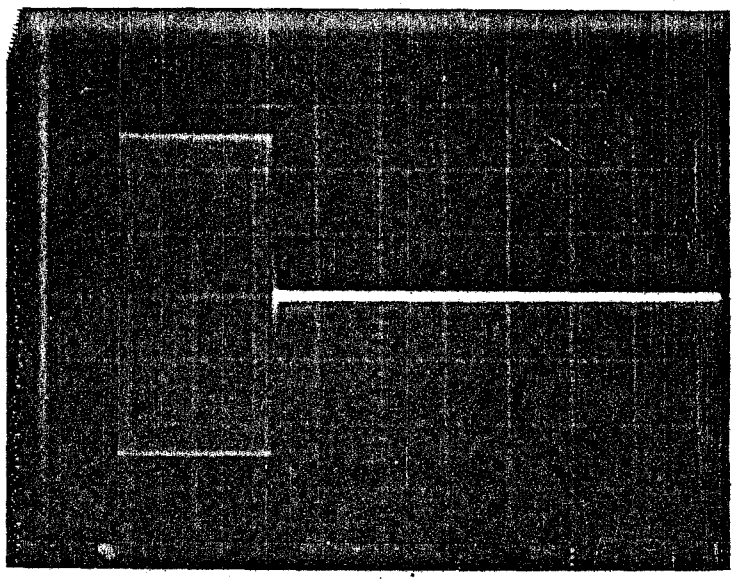


(b)

Figure 1

a) RF envelope of fixed frequency excitation of a booster accelerating cavity below the level of high loss effect onset. Lower trace is phase detector indication of cavity tuning with sensitivity of 20 degrees per division.

b) Same rf envelope and phase information with well developed ferrite high loss effect.



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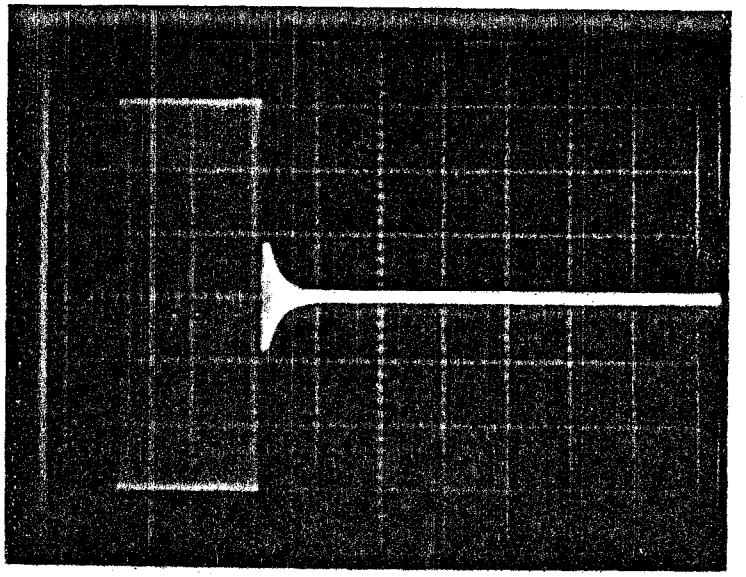

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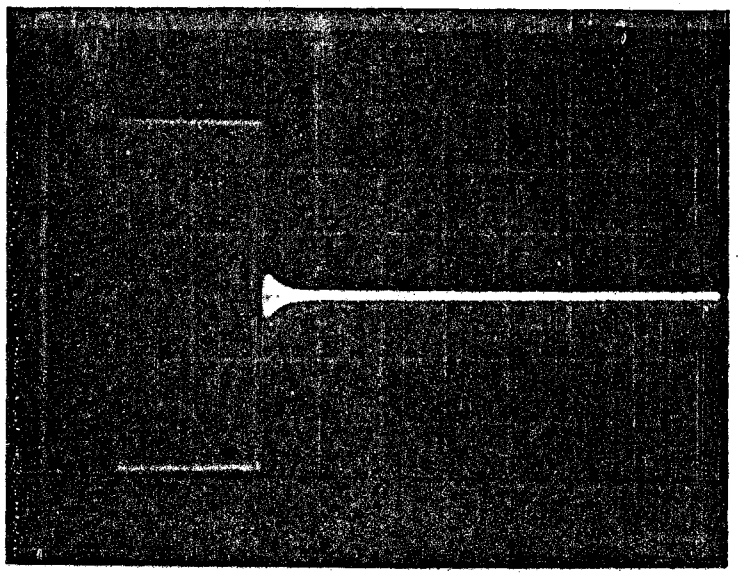
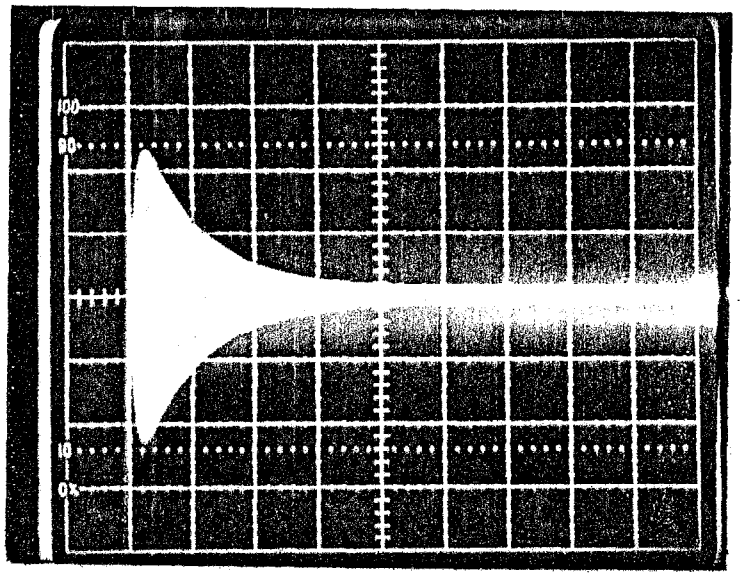


(c)



(d)

Figure 2 Parts a, b, and c. High loss "follow-on" rf bursts with varying degrees of development. Part c. Expanded scale "follow-on" burst, sweep speed 20μsec per division.

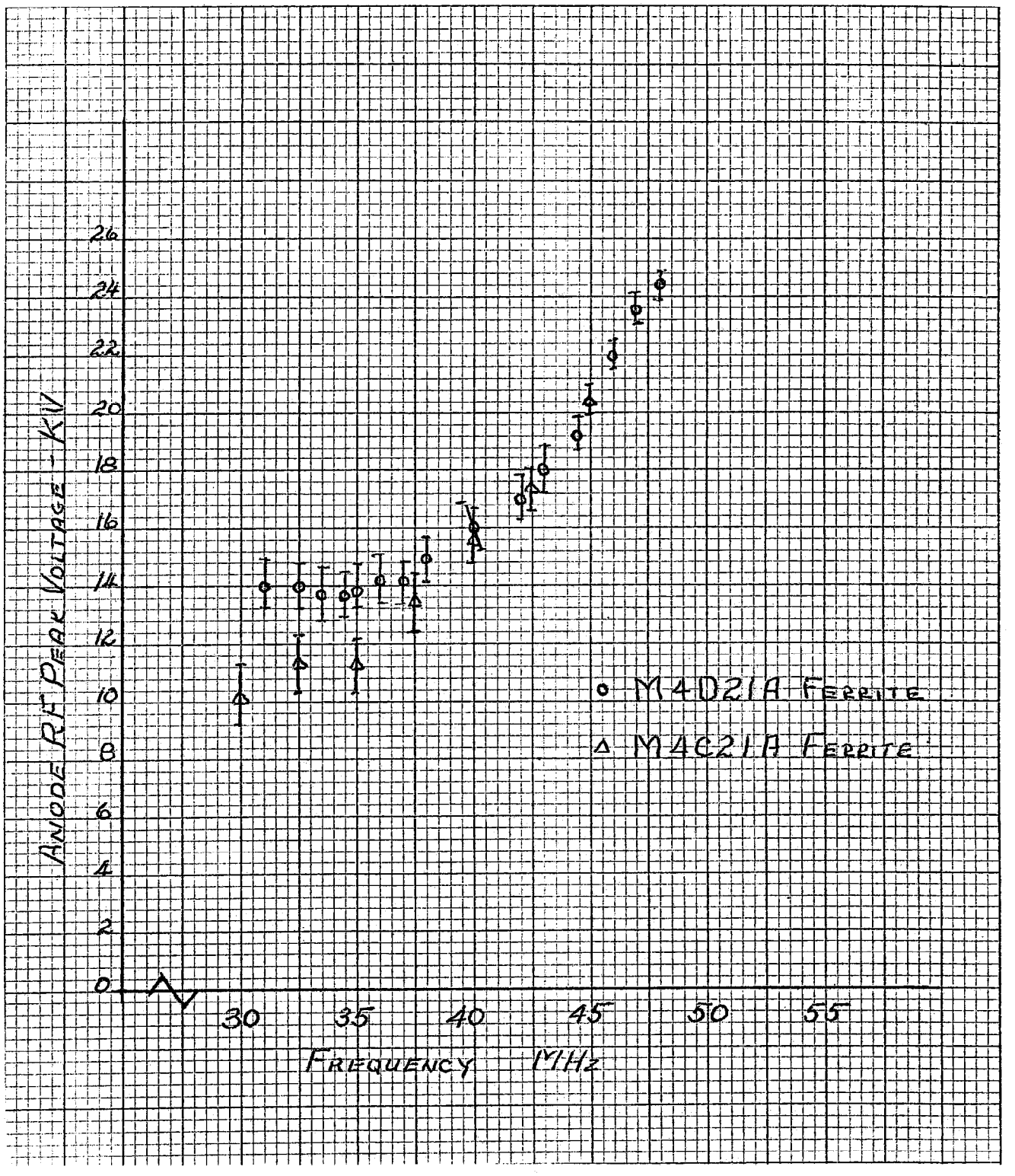


Figure 3

Peak rf voltage swing at the anode of the power amplifier at the threshold for high loss effect plotted as a function of cavity operating frequency.

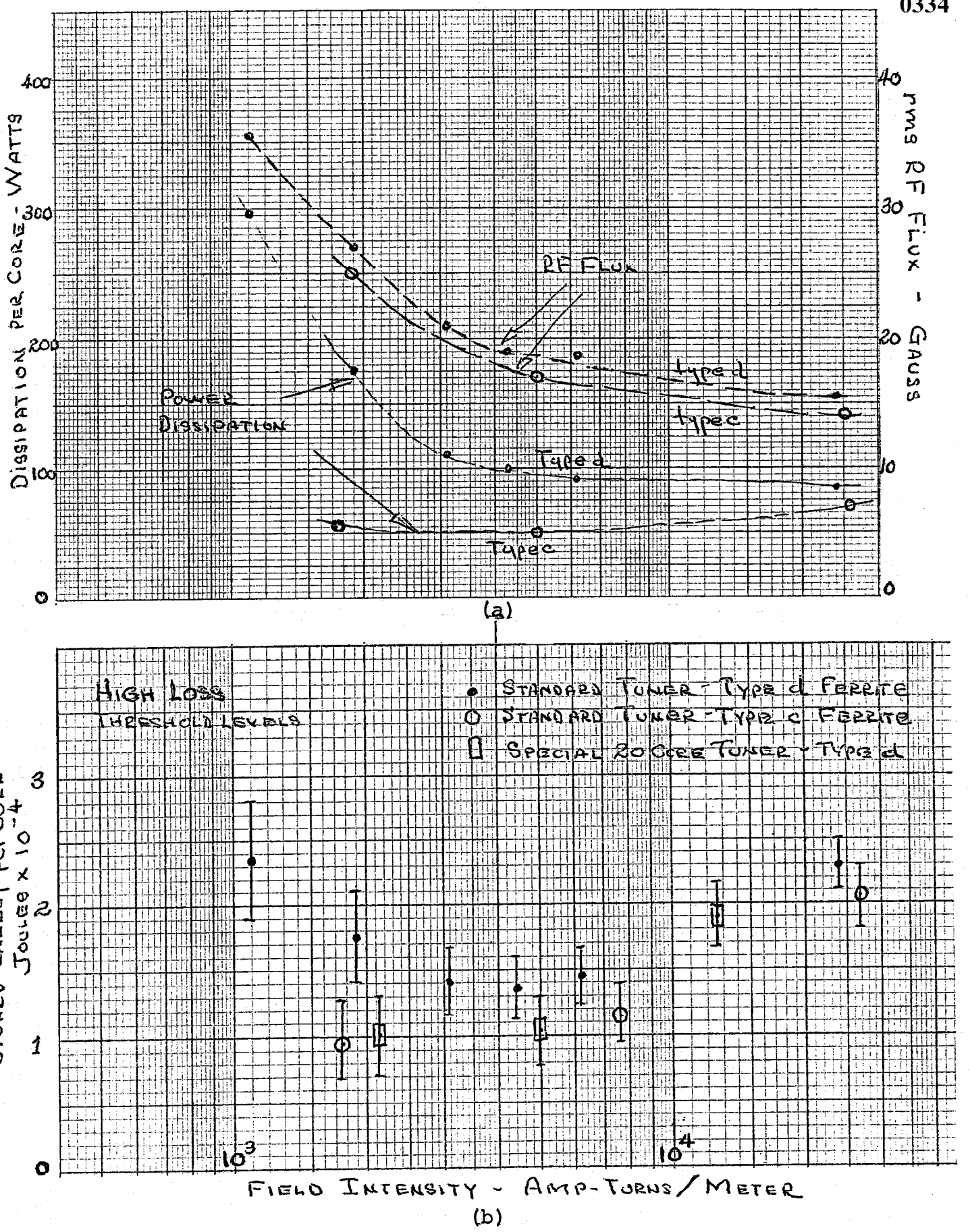
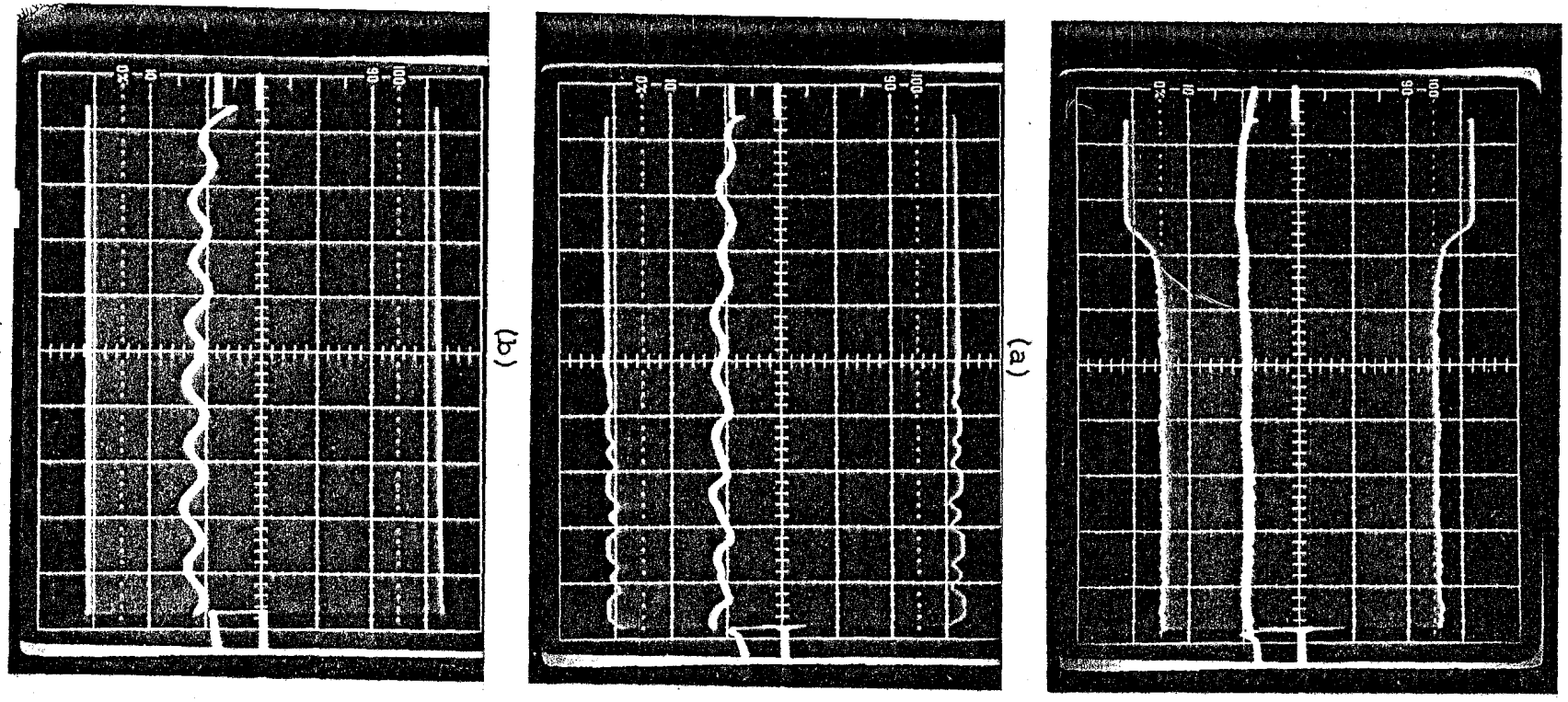


Figure 4 a) RF flux (in Gauss) and power dissipated per core at the onset of high loss effect for M4C21A and M4D21A Toshiba ferrite

b) RF energy stored per core for the two types of ferrite at the threshold for high loss effect

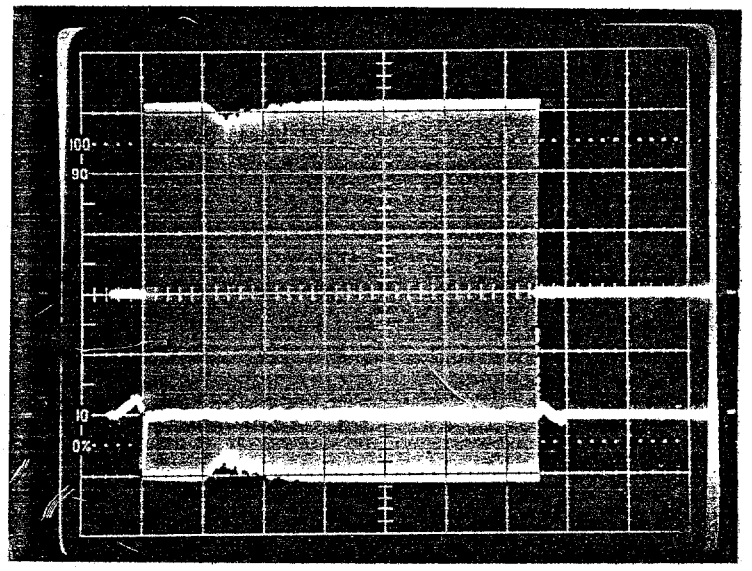


a) Well developed high loss effect at 32.5 MHz with phase error signal. Phase error sensitivity is 30 degrees per division.

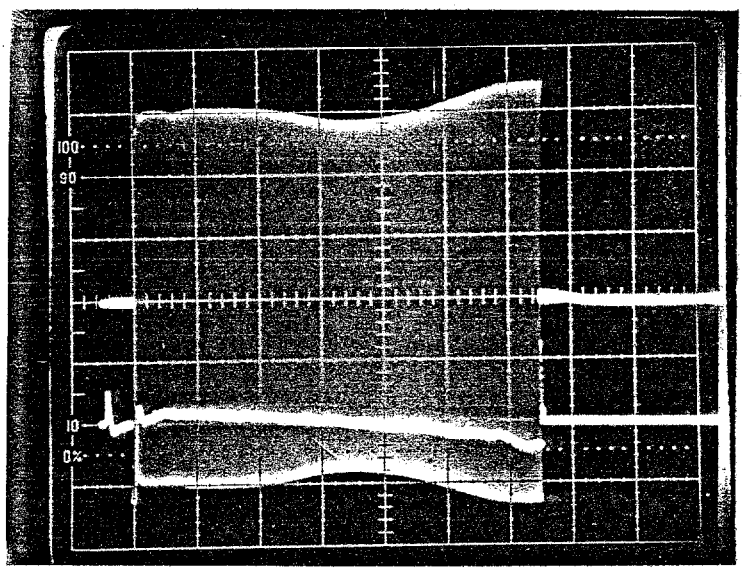
b) Slight reduction of high loss effect by frequency modulation of rf source near 1 kHz.

c) High loss completely eliminated by frequency modulation resulting in phase deviation of about ± eight degrees. Sweep rate is 1 msec per division.

Figure 5



(a)

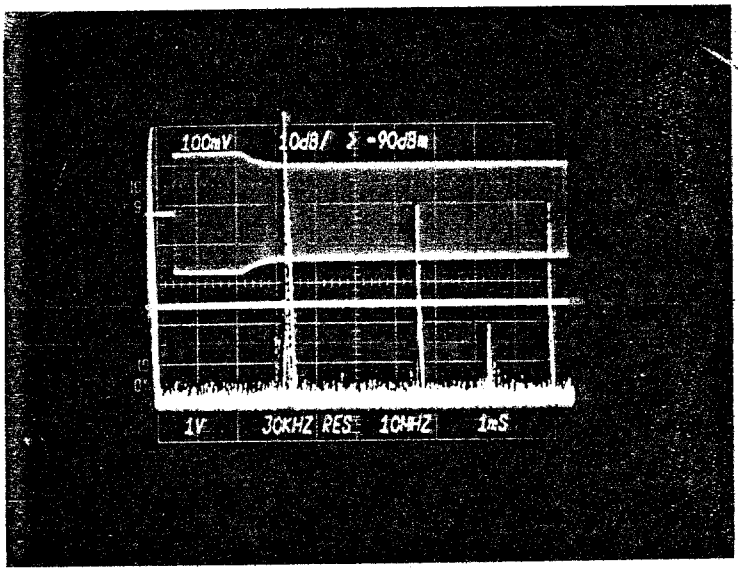


(b)

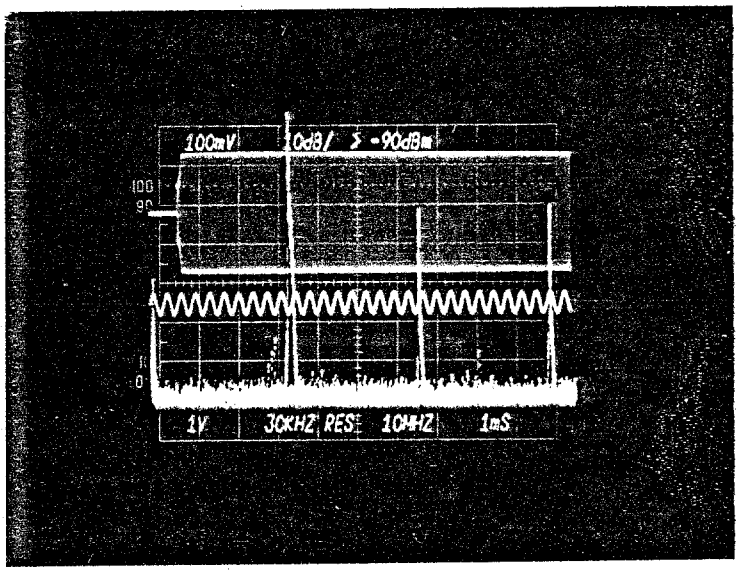
Figure 6

a) High loss effect in the presence of linearly swept frequency. Sweep rate 15 kHz per msec is shown. At rates greater than 18 kHz per msec high loss effect is eliminated.

b) Sweep rate of 200 kHz per msec. The amplitude first decreases because of another effect in the ferrite and later increases due to increased cavity Q at higher ferrite bias.



(a)



(b)

Figure 7

a) Spectrum analyzer signals from broad-band pick-up coupled to cavity fields. The 100 MHz range shows the cavity fundamental frequency 32.5 MHz and its first two harmonics. The strong signal near 84 MHz is thought to be associated with high loss effect which is shown also on the figure.

b) Cavity spectrum with same sensitivity as part a and same rf amplitude excitation. High loss effect has been removed by frequency modulation and 84 MHz signal is absent.

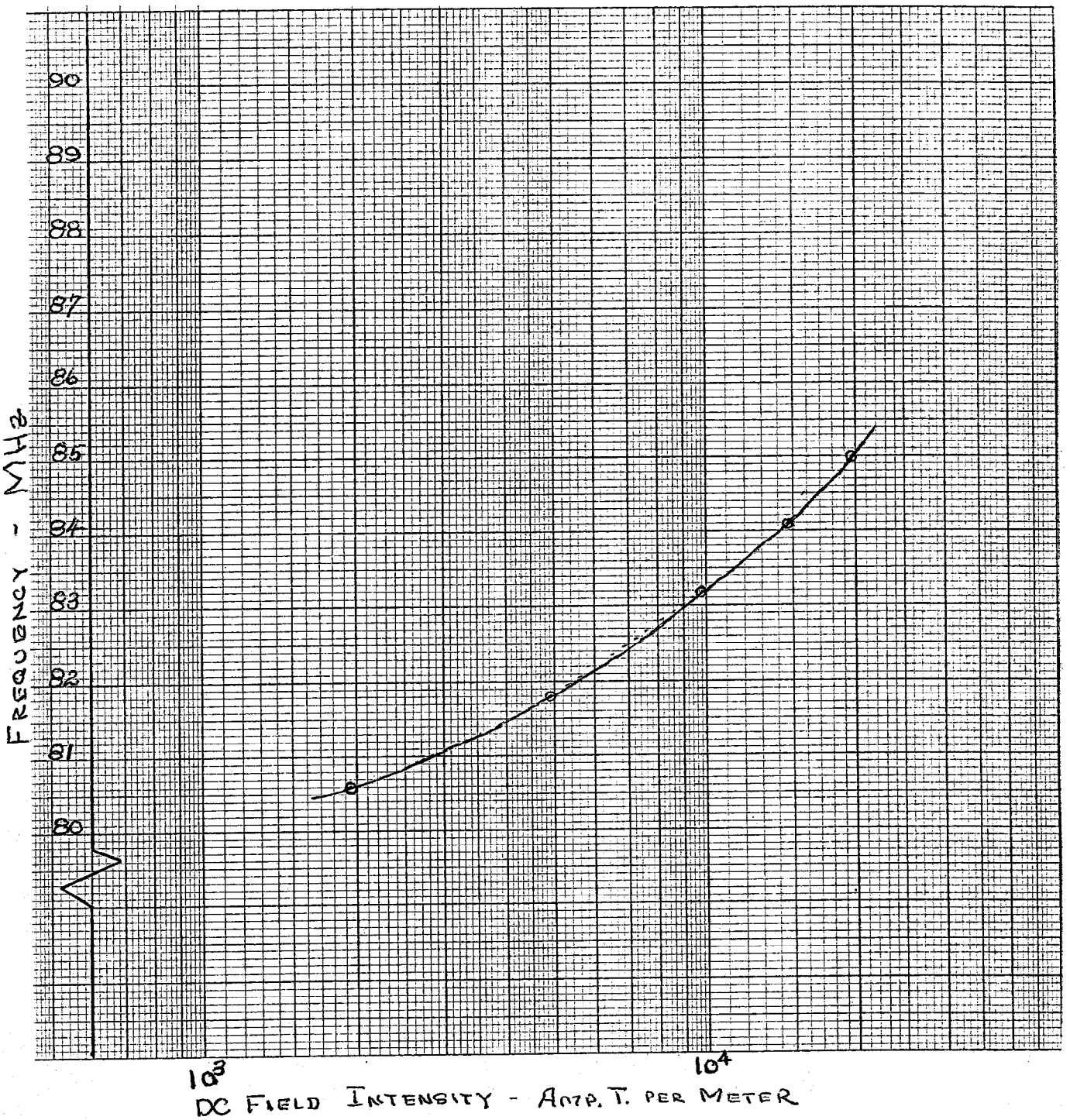

90
89
88
87
86
85
84
83
82
81
80
FREQUENCY - MHz
10^3
10^4
DC FIELD INTENSITY - AMP. T. PER METER

Figure 8